STATUS OF NASA/GSFC KA-BAND ACTIVITIES INCLUDING HIGH DATA RATE DEMONSTRATIONS FOR NEAR-EARTH COMMUNICATIONS

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1. Introduction

The National Aeronautics and Space Administration (NASA) intends to use Ka-band for the transmission of high rate data from near-Earth missions primarily because of concerns over the increasing congestion in the frequency bands that science spacecraft currently use. NASA's Space Network (SN) currently provides communications support at S-band and Ku-band to a variety of science spacecraft via the Tracking and Data Relay Satellite System (TDRSS) spacecraft and the ground assets that are located at the White Sands Complex (WSC). Similarly, NASA's Ground Network (GN) provides communications support at S-band and X-band to science spacecraft via direct links to ground stations that are located worldwide. NASA's forecasts for Earth exploration-satellite (EES) mission requirements reflect the need for telemetry data rates up to 1.0 Gbps and beyond. These escalating data throughput requirements cannot be supported by the SN and GN using the present Ku-band and X-band spectrum, respectively. Additionally, NASA's TDRSS Ku-band forward and return links have secondary allocations from the International Telecommunications Union (ITU). Therefore, fixed satellite service Earth stations transmitting in the Earth-to-space direction will likely generate increasing interference to the TDRSS forward links. In recognition of these constraints, NASA and space agencies of other countries through their administrations have been developing regulatory provisions that will enable a more intense use of the 26 GHz band to satisfy earth science and space science service requirements. The 26 GHz band has a primary allocation from the ITU for both Inter-Satellite Service (ISS) and EES service, and does not suffer from the congestion and interference that has become increasingly likely in the lower frequency bands.

This paper describes a number of complementary activities that have been ongoing within NASA/Goddard Space Flight Center (GSFC) to promote the use of Ka-band for the transmission of high rate data from near-Earth missions. These activities include the procurement of three new Ka-band capable TDRSS spacecraft (TDRS H,I,J), the Ka-Band Transition Project (KaTP) which will implement SN and GN infrastructure upgrades to support wide-band Ka-band services, the development of a space qualified Ka-band phased array antenna, the development of high data rate modulators and demodulators for Ka-band customers, and the development of a space qualified Ka-band solid state power amplifier (SSPA). This paper presents the status of each of these activities. This paper also provides preliminary Ka-band test results for high data rate demonstration tests that were performed under the KaTP.

2. TDRSS Upgrades to Support Ka-Band Service

Starting in 2000, NASA/GSFC launched the first of three new next generation Tracking and Data Relay Satellites (TDRS) known as H,I,J to enhance the Space Network's (SN) support to

Low Earth Orbit (LEO) spacecraft. TDRS H,I,J maintains compatibility with existing customer spacecraft at S- and Ku-bands while adding a Ka-band space-to-space link communications capability. The TDRS H,I,J Ka-band space-to-space links operate in bands that are allocated on a primary basis to Inter-Satellite Service (ISS). NASA currently operates in Ku-band for space-to-space links that are allocated on a secondary basis, therefore NASA may be subject to operational Ku-band restrictions in the future. The Ka-band space-to-space forward link operates in the 22.55 GHz to 23.55 GHz band. The Ka-band space-to-space return link from the customer spacecraft to TDRS H,I,J operates in the 25.25 to 27.5 GHz band. For the Ka-band return link, the TDRS H,I,J spacecraft have two channel options which are the 225 MHz bandwidth channel and the 650 MHz bandwidth channel. Both channels are tunable across the band. The TDRS space-to-ground links continue to operate at Ku-band.

NASA launched TDRS H in June 2000. By February 2002, NASA had fully tested TDRS H which is now operational at a 171 west longitude. NASA launched TDRS I in March 2002. TDRS I is currently undergoing orbit raising maneuvers after which on-orbit payload testing will commence. TDRS J is currently under development. NASA has scheduled the TDRS J launch for October 2002.

The TDRSS ground stations located at NASA's White Sands Complex (WSC) are currently capable of supporting Ka-band customers via TDRS H,I,J at data rates up to 300 Mbps via the TDRS H,I,J 225 MHz bandwidth channel. This capability was implemented by the TDRS H,I,J development contractor. However, the WSC cannot support the Ka-band wideband return link (650 MHz bandwidth channel) which is provided by the TDRS H,I,J spacecraft. This high rate return capability at WSC was not required as part of the TDRS H,I,J development contract and was left for NASA to implement at a later date.

3. NASA's Ground Infrastructure Upgrades to Support Ka-Band Service

In early 2000, NASA/GSFC established the Ka-Band Transition Project (KaTP) to develop and implement the necessary network infrastructure for demonstrating and supporting high data rate SN and GN Ka-band data services. The project is implementing a new Ka-band ground station for the GN to support high data rate demonstrations. The project is also modifying the SN ground stations at the WSC to support a Ka-band wide-band return link that uses the TDRS H,I,J's 650 MHz bandwidth channel. When the SN implementations are complete in the second half of 2002, NASA will perform high data rate SN demonstrations (600 Mbps) by using a high data rate receiver and a demonstration high data rate transmitter.

NASA has completed the majority of the GN Ka-band ground station integration and testing, and has conducted preliminary Ka-band loop-back GN demonstration tests at 300 Mbps and 600 Mbps. The GN acceptance testing is scheduled for August 2002 and high data rate Ka-band demonstrations will follow the acceptance testing. When complete, this project will provide the results and impetus to guide the future direction for Ka-band high rate data service provisioning.

3.1 Space Network Implementation

NASA is upgrading the SN ground stations at the WSC (New Mexico, USA) to take advantage of the new TDRS H,I,J spacecraft 650 MHz bandwidth channel for Ka-band space-to-space return links in the 25.25 GHz to 27.5 GHz band. The WSC ground stations are presently only capable of supporting Ka-band customers via TDRS H,I,J at data rates up to 300 Mbps using the TDRS H,I,J spacecraft 225 MHz bandwidth channel for Ka-band space-to-space return links. Table 1 lists the key parameters of the SN 650 MHz-wide Ka-band service that NASA is enabling under the KaTP.

NASA is implementing a prime and redundant 650 MHz bandwidth channel Intermediate Frequency (IF) service at four of the five Space-Ground Link Terminals (SGLTs) by adding new downconverters and waveguide equalizers. The downconverters will receive the 650 MHz-wide Ku-band downlink signal from TDRS H,I,J spacecraft and will output a 1200 MHz IF signal. The IF signals will be fed into an IF switch for routing to a high data rate receiver. An equalizer will correct phase and amplitude distortions that result when wide-band signals propagate through the long WSC Ku-band waveguide runs.

Also, NASA is modifying the existing WSC 225 MHz bandwidth channel prime and redundant downconverters to support two different Ka-band frequency plans. The two plans supported are the TDRS H,I,J frequency plan and the Space Networks Interoperability Panel (SNIP) frequency plan [3]. The SNIP Ka-band frequency plan contains Ka-band forward and return center frequency recommendations for space-to-space link communications via data relay satellites. The SNIP developed their Ka-band frequency plan in order to promote interoperability among NASA, European Space Agency (ESA), and National Space Development Agency of Japan (NASDA) space networks. Additionally, NASA is modifying the software and firmware at WSC to support the scheduling, control, and monitoring of the new and modified hardware.

Table 1. Key Ka-Band Parameters for SN and GN

Parameter	SN Requirement	GN Requirement
1. Frequency Range	25.25 to 27.5 GHz	25.5 to 27.0 GHz
2. Antenna G/T	26.5 dB/K, TDRS autotrack mode	32.5 dB/K; clear sky, 10° elevation
3. Axial Ratio	1.0 dB maximum	2.0 dB maximum
4. Polarization	RHC or LHC; selectable	RHC or LHC; selectable
5. Radial Tracking Error	N/A	0.05 degrees; 1 sigma
6. RF Channel 3 dB Bandwidth	650 MHz	1200 MHz
7. IF Output Center Freq.	1200 MHz	1200 MHz
8. Tuning Step Size	SNIP Frequency Plan [3]	125 kHz
9. Gain Flatness	≤ 1.0 dB peak-to-peak over ±230 MHz about IF (WSC ground terminal)	≤ 2.0 dB peak-to-peak over ±420 MHz about IF
10. Phase Nonlinearity	≤ 30° peak-to-peak over ±230 MHz about IF (WSC ground terminal)	≤ 10° peak-to-peak over ±420 MHz about IF

3.2 Ground Network Implementation

NASA is installing a single GN Ka-band ground station at the NASA/GSFC Wallops Flight Facility (WFF) in Virginia, USA, to support unified S-Band command (2025 to 2120 MHz) and telemetry (2200 to 2300 MHz), and Ka-Band telemetry (25.5 to 27.0 GHz). Table 1 lists some of the key parameters of the ground station's Ka-band receive system.

The ground station consists of a 5.4 meter X-Y mount antenna which is housed in a radome with a Ka-band cassegrain feed and a S-band prime focus feed. The Ka-band ground station equipment provides an IF output at 1200 MHz with an interface that is identical to the SN

Ka-band IF output. The ground station supports simultaneous Ka-Band and S-band telemetry receive, S-band command transmit, and S-band and Ka-band antenna autotrack. Current plans call for the Ka-band ground station to be used only for demonstration purposes when complete.

3.3 High Data Rate GN and SN Demonstrations

The KaTP GN high data rate demonstrations will utilize the new equipment implemented within the GN Ka-band ground station to demonstrate the GN capability to support LEO spacecraft at Ka-band with data rates of at least 600 Mbps. The KaTP SN high data rate demonstrations will use the new equipment implemented in the WSC ground terminals to demonstrate the SN capability to support LEO spacecraft at Ka-band with data rates of at least 600 Mbps.

Figure 1 illustrates the planned configuration for full Ka-band end-to-end high data rate GN demonstrations. NASA will perform the end-to-end GN demonstrations using a boresite tower equipped with a Ka-band transmitting system. The Ka-band transmitting system will consist of a pseudo-noise (PN) data generator, high-rate test modulator, variable attenuator, a Ka-band upconverter, and antenna. The boresite tower is approximately two kilometers from the Ka-band ground station

To date, NASA has performed preliminary loop-back GN demonstrations with the GN ground station equipment to assess the RF link performance via measurements of bit error rate (BER) and the signal spectra. Figure 2 illustrates the GN demonstration configuration that was used to obtain Ka-band loop-back BER data. NASA performed these measurements at 300 Mbps and 600 Mbps. For both data rates, the output power from the Ka-band modulator was varied in steps in order to vary the E_b/N_0 for BERs between 10^{-5} and 10^{-8}. BER vs. E_b/N_0 curves, which are shown in Figure 3, were developed using at least three data points for each data rate. As seen from the curves in Figure 3, when operating at a 10^{-5} BER, the Ka-band loop-back implementation loss varies from 2.4 dB at 300 Mbps to 3.2 dB at 600 Mbps.

The high data rate SN demonstrations are currently scheduled for the fall of 2002. Figure 4 is a high-level block diagram of the planned SN demonstration configuration. Similar to the GN demonstrations, the SN demonstrations will assess the Radio Frequency (RF) link performance via measurements of BER and the signal spectra. The SN demonstration will use the TDRS H or I spacecraft to relay the signal to a SGLT at the WSC. The SN demonstrations will utilize WSC on-site test equipment including the existing Ka-band Test Transmitting System used for TDRS H on-orbit payload testing. This test transmitting system currently simulates a Ka-band Single Access Return (KaSAR) customer at ≤300 Mbps on the 225 MHz bandwidth channel, however it is being modified to simulate KaSAR customers operating at 600 Mbps using the 650 MHz bandwidth channel. The KaTP project is also investigating the use of potential targets of opportunity such as the ENVIronmental SATellite (ENVISAT) spacecraft for additional Ka-band demonstrations.

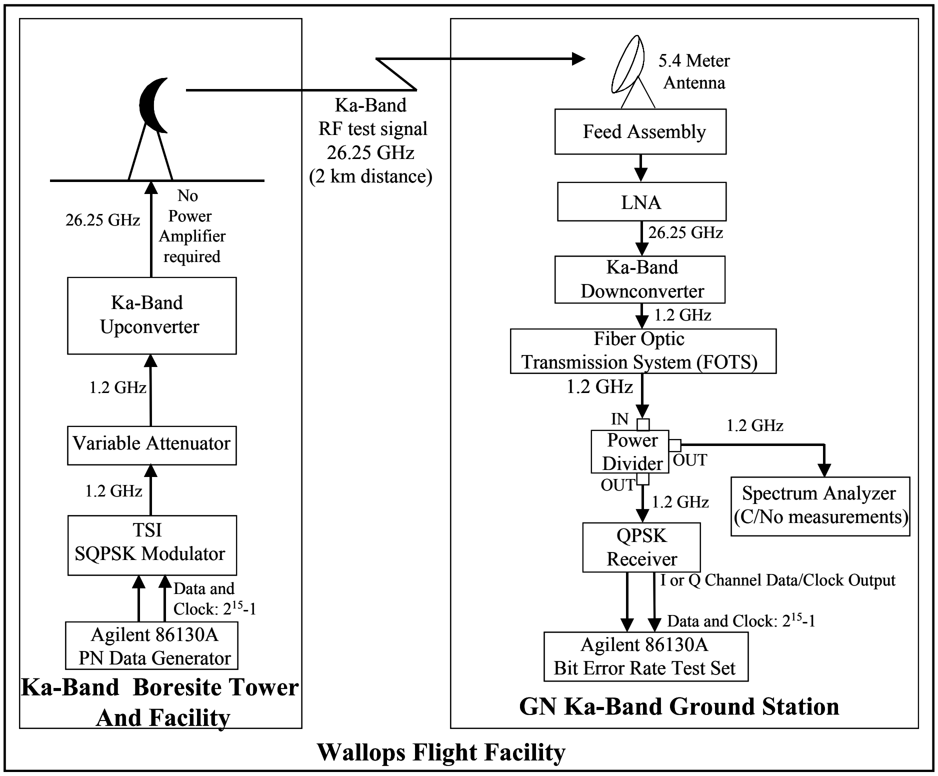

Figure 1. Planned Ka-Band GN End-To-End Demonstration Test Configuration

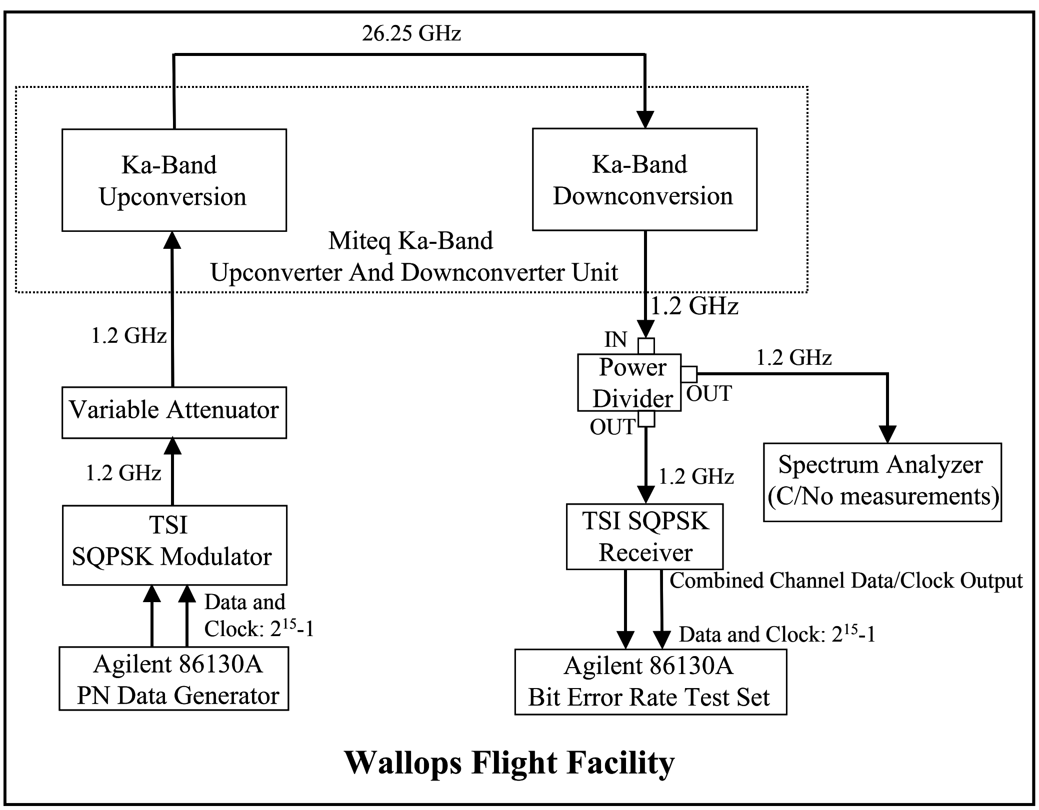

Figure 2. Completed Ka-Band GN Demonstration Loop-Back Test Configuration

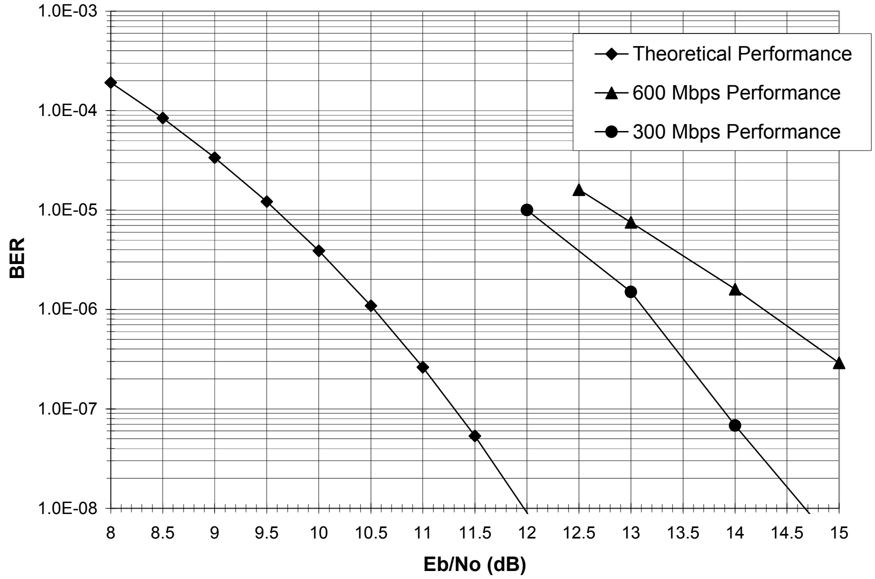

Figure 3. Ka-Band GN Loop-Back Demonstration Test Results (Preliminary)

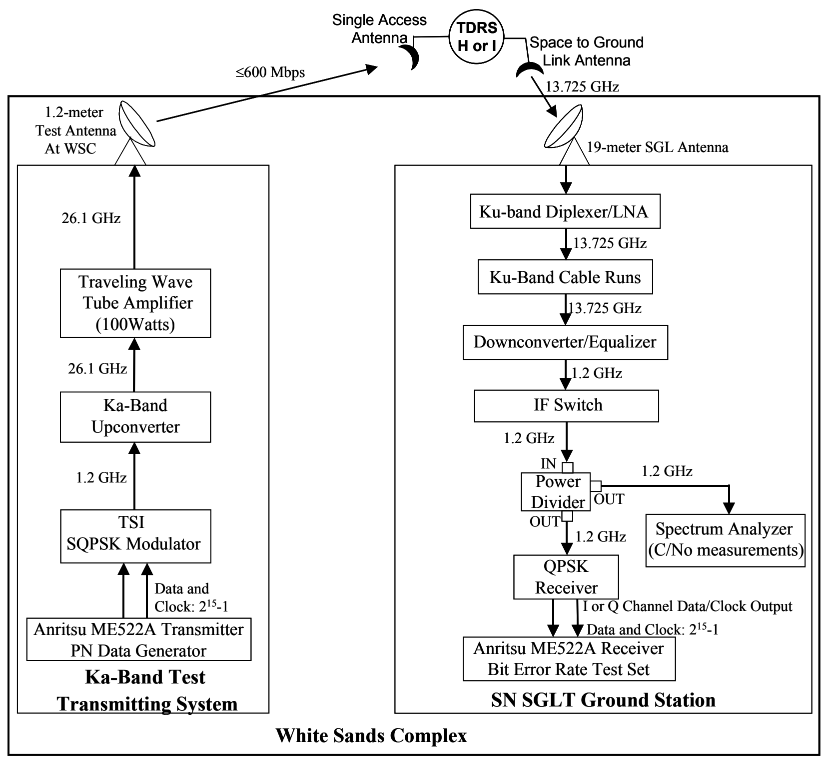

Figure 4. Planned Ka-Band SN End-To-End Demonstration Test Configuration

4. Ka-Band Technology Developments At NASA/GSFC

To further encourage future NASA missions to make the transition from the current S, X, and Ku-band allocations to Ka-band, NASA has developed a comprehensive Technology Roadmap. The Roadmap addresses the requirements of a wide variety of NASA mission types by identifying multiple alternative Ka-band communications systems architecture concepts. For each architecture concept, the Roadmap identifies the applicable system and component level requirements, assesses the current state of the art in Commercial Off-The-Shelf (COTS) products, highlights the additional necessary Ka-band component/subsystem developments, and provides a strategic plan for future technology investments. This section discusses the following four ongoing GSFC technology development activities that promote the use of Ka-band by future NASA missions:

- The Ka-Band Phased Array Antenna
- The High Data Rate Parallel Digital Receiver
- Ka-Band High Data Rate Modulators
- Ka-Band SSPA

4.1 Ka-Band Phased Array Antenna

The High Rate User Ka-Band Phased Array Antenna (HRUPAA) was developed for NASA/GSFC by Harris Corporation, (Florida, USA). A partially populated engineering model antenna was delivered to GSFC in late 2000. NASA verified the antenna beam steering control, antenna patterns, and Effective Isotopic Radiated Power (EIRP) using both the GSFC Compact Range Facility and Near Field Range. Table 2 provides the characteristics of the fully populated antenna. [4,5]

NASA is currently planning HRUPAA/GN Ka-band Ground Station 600 Mbps tests to evaluate the HRUPAA performance in an actual high data rate communications system. The HRUPAA test configuration will be almost identical to the GN demonstration depicted in Figure 1. 600 Mbps is an achievable data rate because the HRUPAA has a wide 800 MHz bandwidth. NASA will characterize performance at scan angles of 0°, 30°, and 60°. NASA will also characterize the performance at different HRUPAA RF input levels.

Table 2: Ka-band Phased Array Antenna Characteristics

Parameter	Value
1. Frequency Range	25.25 to 27.5 GHz
2. 3 dB Bandwidth	± 400 MHz
3. Scan Range	± 60 degrees
4. Size (mass, volume)	≤ 5.2 kg, ≤ 8.8 x 6.9 x 5.8 (W x H x D) inches
5. Polarization	Left-Hand Circular Polarized, 11 dB Cross-Polarization Isolation
6. Output Power	33 dBW EIRP
7. Power Consumption	<82 Watts
8. Max Achievable Data Rate (QPSK)	350 Mbps is specification requirement, however NASA is planning 600 Mbps QPSK tests using the KaTP GN Ground Station.

4.2 High Data Rate Parallel Digital Receiver

NASA/GSFC is developing a digital "software" receiver, capable of supporting data rates up to 600 Mbps. The receiver's analog front-end unit initially conducts downconversion from the 1200 MHz IF to a frequency that is a function of the symbol rate, but the receiver conducts almost all other functions digitally on a single PC card. The receiver digitizes the signal after downconversion to the symbol rate dependent IF frequency. Then the receiver performs demodulation and data detection digitally on the sampled data using high speed Application Specific Integrated Circuits (ASICs). The digital demodulator [6] is implemented as a PC card, with a standard PCI interface for configuration and control. The digital implementation results in a more reliable product with an anticipated very low replication cost.

The current version of the receiver operates at rates up to 600 Mbps and supports the BPSK, QPSK, SQPSK, and Unbalanced QPSK (UQPSK) modulation formats. The next generation High Data Rate Parallel Digital Receiver will increase the maximum data rate up to 1.2 Gbps and will add support for higher order bandwidth efficient modulations (such as 8-PSK and 16-QAM). NASA plans to use the current (600 Mbps) version of this receiver as the primary high data rate receiver for its KaTP GN and SN end-to-end demonstrations which were discussed in section 3 of this paper.

4.3 Ka-Band High Data Rate Modulators

NASA has recently initiated the development of a prototype, ultra-high rate, re-programmable, all-digital baseband modulator which will be capable of generating a variety of bandwidth efficient waveforms and modulations for data transmission over various RF channels (X-band, Ka-band, etc.). Scheduled for completion in FY05, the modulator will be based upon Complementary Metal-Oxide-Semiconductor (CMOS) parallel designs that can be cascaded to achieve arbitrarily high sample and symbol rates. The architecture will be capable of generating a number of advanced constant envelope modulations and bandwidth efficient modulations, including Consultative Committee for Space Data Systems (CCSDS) recommended Feher QPSK (FQPSK), CCSDS recommended Gaussian Minimum Shift Keying (GMSK), TCM 8-PSK, and other variations of QPSK. The high rate bandwidth efficient modulator prototype will be developed for an eventual migration to a space qualified design.

NASA has also developed a QPSK Ka-band modulator for the Solar Dynamics Observatory (SDO) mission that operates at data rates up to 300 Mbps and provides an output directly at the space science allocated Ka-band frequencies. NASA/GSFC is currently conducting laboratory testing on an engineering model in order to characterize the modulator's electrical and BER performance.

4.4 Ka-Band SSPA

NASA and Morgan State University (MSU) are conducting a joint team effort to develop Solid State Power Amplifiers (SSPAs) at X-band and Ka-band. The SSPAs will utilize wide band gap semiconductors such as SiC, SiGe or GaN. MSU is currently investigating the DC and RF characteristics of SiC, SiGe and GaN semiconductor devices that they will use to develop a neural network model for the SSPAs that use those devices. A proof-of-concept Monolithic Microwave Integrated Circuit (MMIC) amplifier at X-band will be developed and tested using the neural network model of these devices. The X-band test data and the neural network model will be extrapolated to Ka-band to assess its performance for Ka-band application. NASA plans to develop, fabricate, and test a Ka-band MMIC SSPA in 2004.

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